To: Brandon Goshi, MWD
Subject: Downscaled Climate Data for IRPsim Modeling
From: David Groves and Robert Lempert, RAND
Date: March 9, 2009

Introduction

This memo recommends an approach for incorporating climate change impacts into IRPsim planning analyses for MWD's next IRP. It first provides a very brief summary of MWD's current methodology. Next it describes an approach for evaluating climate change using IRPsim. Finally, it describes climate data which has been compiled for this purpose by the consulting team.

Current Methodology

MWD currently estimates its ability to supply needed water to its member agencies from the present to several decades into the future (e.g. to 2030 or 2040). MWD estimates retail demand using an econometric-based model, MWD-MAIN, and information from agricultural surveys. Local available supply is estimated through member agency surveys and output from Los Angeles's LAASim Aqueduct Model and Orange County Water District's Groundwater Model. Available imported supply and storage is estimated using output from the USBR's CRA Model of the Colorado River system, output from DWR's model of the State Water Project (CalSim), and a model of local and regional storage programs. MWD's IRPsim integrates these results and analysis. Simulations also reflect the addition of new storage, efficiency, transfers, and other management options.

Projections of future demand, local supplies, and available imports all depend on the projected weather and associated hydrologic conditions. IRPsim estimates the performance of the management system under a series of 83 sequentially-indexed hydrology/climate conditions (1922-2004). Assuming that each indexed hydrology/climate sequence is equally likely, these quantities are averaged over the 83 trials to estimate system reliability.

This approach is well suited for analyses that can make the following three assumptions:

- **Historical conditions are the best guide to future conditions.** This must be true to use historical conditions as a proxy for future conditions.
- **No long-term trends are present in the historical record**. Because the 83 hydrologic sequences are created by looping through the historical sequence using different start years, the nature of the beginning of the hydrologic sequence must be similar to that of the end sequence. In other words, the hydrologic conditions for 1922 must be similar to 2004, otherwise there will be a discontinuity for the time steps that are represented by the 2004 and 1922 data.
- **No trends are anticipated in the future**. This assumption follows from 1 and 2. Since no trends can exist in the historical record for the sequential indexing

methodology to work, one cannot use this method to evaluate future hydrologic conditions that have trends.

Climate change analyses break each of these assumptions: (1) a changing climate suggest that future conditions will be different than historical conditions, (2) even the historical record could be exhibiting changes, potentially introducing discontinuities when using the most recent historical-data, and (3) climate change trends in hydrologic parameters are of key interest and thus must be included.

An approach for incorporating climate change in IRP projections

The IRP consulting team proposes a multi-faceted approach to incorporating climate change into IRP analysis. At its core, our proposed approach evaluates water management strategies under a wide range of plausible climate scenario, as suggested by the world's leading global climate models. Ideally, each supply and demand component within IRPsim would be evaluated under new sequences of monthly weather (temperature and precipitation). Weather scenarios internally consistent across space and time would be derived from global projections of atmosphere-ocean general circulation models (GCMs). Uncertainty about future conditions would be reflected through the consideration of a large ensemble of different GCMs and underlying forcing parameterizations (e.g. global greenhouse gas emissions scenarios). As described below, the consulting team has developed new hydrologic sequences on a 1/8 degree grid against which MWD demands and supplies can be evaluated.

The IRP modeling suite must also be revised to incorporate this alternate specification of climate conditions. For local demand and local supply estimations, this requires deriving new relationships between projected weather conditions and demand and available supply. For SWP, LAA, and CRA imported supply, the consulting team proposes using alternative scenario-based models to develop estimates of imported supply that is commensurate with the local climate scenarios.

Developing hydrologic sequences

There are a variety of options for developing hydrologic sequences reflective of climate change for use in IRPsim. Some options include:

Evaluate IRPsim using single sequences of down-scaled GCM weather projections. GCM-projected sequences cannot be indexed and evaluated multiple times to generate statistics as there would be discontinuities where the sequence repeats. Therefore each GCM simulation could only produce a single IRPsim run. Although most GCMs have been run multiple times, there is not a dataset of downscaled simulations available with enough runs to derive annual statistics based on a single GCM that are commensurate with those derived using historical hydrology and the sequential indexing method.

Derive statistics using the suite of GCM simulations. Datasets comprised of downscaled data from a few simulations for 16 GCMs are available and each could be run through IRPsim and be used to develop statistics for each simulation year. The largest problem with this method is that it will produce a single "weighted" climate change response. One would have to assume that the current set of GCM runs are a representative sample of what will be the true climate change effects and that one can assign acceptable weights to each simulation included in the ensemble.

Derive a suite of synthetic sequences that contain similar temperature and precipitation trends to the GCM projections. RAND has partnered with NCAR for past projects to employ this method (Groves et al. 2008). Advantages include the ability to develop an arbitrarily large set of sequences. Disadvantages include larger costs and time required to develop the data and increased unfamiliarity of stakeholders to the methodology.

Derive a suite of simulations for each GCM projection using perturbation ratios. Each GCM projection would be decomposed into its long-term trend and remaining perturbations.

Var_t = var_trend_t + var_perturbation_t

where Var = {Average temperature, precipitation}.

Since the perturbation sequence will exhibit no trend, one could then develop a large set of perturbation sequences using the sequential indexing method, just as is currently done with the historical climate. Note that this method assumes that there is no significant change in the interannual variations of the climate parameters—only in the long-term trend.

The figure below (Figure 1) shows a single GCM average temperature projection (for a Northern California site) for the Micro_3.2 model run under the A2 emissions scenario (solid blue), the trend component (red dashed line), and a 3-year offset projection (dash-dot green). It is straightforward to use the sequential index method to develop 46 different sequences of temperature and precipitation.

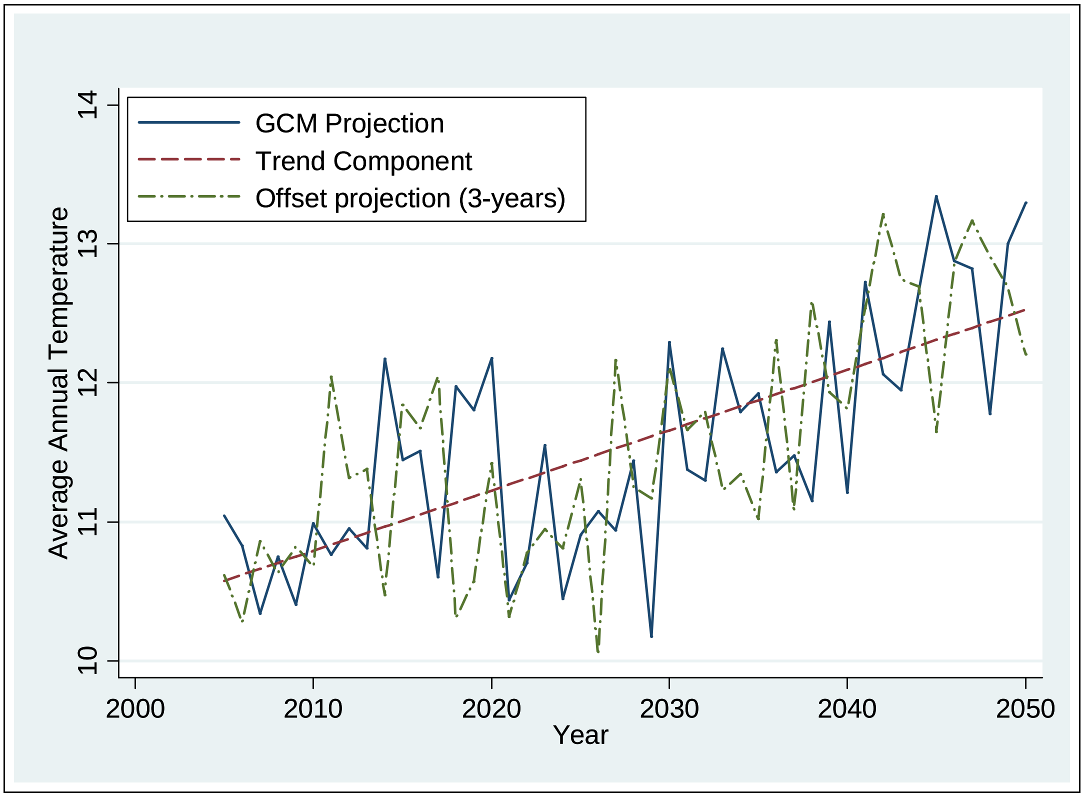


Figure 1: Annual average temperature for a single GCM projection (solid blue line), its linear trend (red dashed line), and a 3-year perturbation offset projection (green slash-dotted line).

Note that each GCM-emissions scenario pair could be used to develop a set of these results, constituting a “climate scenario”. Currently downscaled data exist for one to several runs of 16 GCMs for 3 emissions scenarios (112 pairs) on a 1/8 degree grid.

We propose to that MWD use the fourth option as it preserves the sequential indexing methodology already in use by IRPsim (and CALSIM). We recommend focusing on the 12 GCM/emission scenarios pairs selected by the CEC for the basis of their climate studies although the consulting team will provide data for all GCM/emission scenario pairs.[1]

Future applied water demand

New relationships between projected climate conditions and applied water demand will need to be developed. MWD is currently taking the lead in performing this task and will update the consulting team on on-going progress. As the demand is calculated in aggregate by county, the consulting team has developed associated county-aggregated climate change projections as described in the Data Processing section below.

[1] The CEC is using GCM simulations for the A2 and B1 emissions scenarios for the following models: CNRM CM3, GFDL CM2.1, MIRO3.2 (med), MPI ECHAM5, NCAR CCSM3, NCAR PCM1.

Local supplies

In general, IRPsim includes estimates of local supply availability (generally from groundwater basins) corresponding to each of the different historical years (from 1922-2004). Metropolitan staff are evaluating options for replacing these one-to-one relationships with formula that would derive supply availability in response to a specific sequence of monthly temperature and precipitation projections. The consulting team awaits additional information from MWD on the existing modules and/or relationships that require modification to respond.

State Water Project supplies

The consulting team proposes to develop a WEAP-based water management model of the California State Water Project system to estimate monthly SWP deliveries to MWD under climate scenarios equivalent to those used to evaluate local demand and supply impacts. This WEAP model will be an expanded version of the Sacramento River and San Joaquin River models under development for the California Water Plan as described in the attached memo from Stockholm Environment Institute (dated January 20, 2009).

Colorado River Aqueduct supplies

MWD is currently assessing the availability of independent projections of Colorado River Aqueduct deliveries to MWD under climate change conditions to use for the IRPsim modeling. These estimates should provide a plausible range of CRA deliveries, although they may be based on a different subset of climate change scenarios than the comprehensive set being used for the California-based supply analyses. The consulting team suggests that because the Colorado River system is spatially distinct from the California-based supplies, these independent estimates can still be evaluated alongside the California-based climate impacts within IRPsim. The consulting team will provide more detailed suggestions for doing so once the source of CRA delivery estimates are identified.

Los Angeles Aqueduct supplies

The consulting team has developed a proposal to LADWP for conducting a comprehensive assessment of climate impacts upon LADWP's Los Angeles Aqueduct system. This proposal included developing an upper-watershed WEAP model of the Owen's valley and updating the LA Aqueduct Simulation Model (LAASM) to evaluate these new climate-impacted inflows. LADWP chose to support an alternative approach. MWD is currently in discussions with LADWP about the possibility of sharing data and cost-sharing portions of our approach for use in the MWD IRP. The consulting team awaits an update on these conversations.

Climate Data for Local Supplies and Demand Analyses

Data Sources

The consulting team obtained downscaled monthly temperature and climate projections from the LLNL-Reclamation-SCU downscaled climate dataset (http://gdo-dcp.ucllnl.org/). These data were derived from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset and include data from 112 different global climate simulations of 16 global models evaluated for three global emissions scenarios. The projections are available from 1950 to 2099 (data for past time periods are back-casted). This dataset includes the 12 projections chosen by the California Climate Action Team (Cayan et al. 2006) as a representative sample of GCM projections for California climate studies. For this study we use only the forward projections from 2000 – 2050.

For historical data, we obtained monthly averaged daily gridded meteorological data from the Surface Water Modeling group at the University of Washington (http://www.hydro.washington.edu/Lettenmaier/Data/gridded/—see Maurer et al. (2002) for a description of the data). This data set includes daily precipitation, maximum daily temperature, minimum daily temperature, and average daily wind speed from 1949 to 2000. These historical data were used in the downscaling procedure used by the LLNL-Reclamation-SCU analysis, so the historical data are directly comparable to the projected data.

Data Processing

We obtained historical and projected data for each 1/8 degree grid location in the MWD service area. We average the historical maximum and minimum daily temperature to derive average monthly temperature to compare to the projected data, and we sum the daily precipitation to develop projections of monthly precipitation. Together these data comprise time sequences of average monthly temperature and precipitation from 1950 to 2050 (with the data from 1950 – 2000 being based on the historical record).

To develop single sequences for each county for use in the demand analysis we spatially-average the monthly temperature and precipitation data for each grid point in each county. As shown below, there is significant spatial heterogeneity across the Southern California counties—reflecting, in large part, the difference in elevation across the counties. As most of the applied water demand is concentrated in the low-lying regions with distinctly different patterns of weather variability, we also use GIS data from the 2006 National Land Cover Data set (www.epa.gov/mrlc/nlcd-2006.html) as available from the USGS National Map Seamless Server (seamless.usgs.gov/index.php) to identify those 1/8 degree grid points that best reflect the urban and suburban regions of each county. We then developed averages of only these grid points. We propose using these data for the demand analysis.

Finally, we have also developed the processing algorithms to derive the sequentially indexed sequences for each GCM-derived weather sequences required for the IRPsim modeling.

Climate Data Summary Analysis

Figure 2 shows the grid points overlying the MWD service area (green area) and overall watershed.

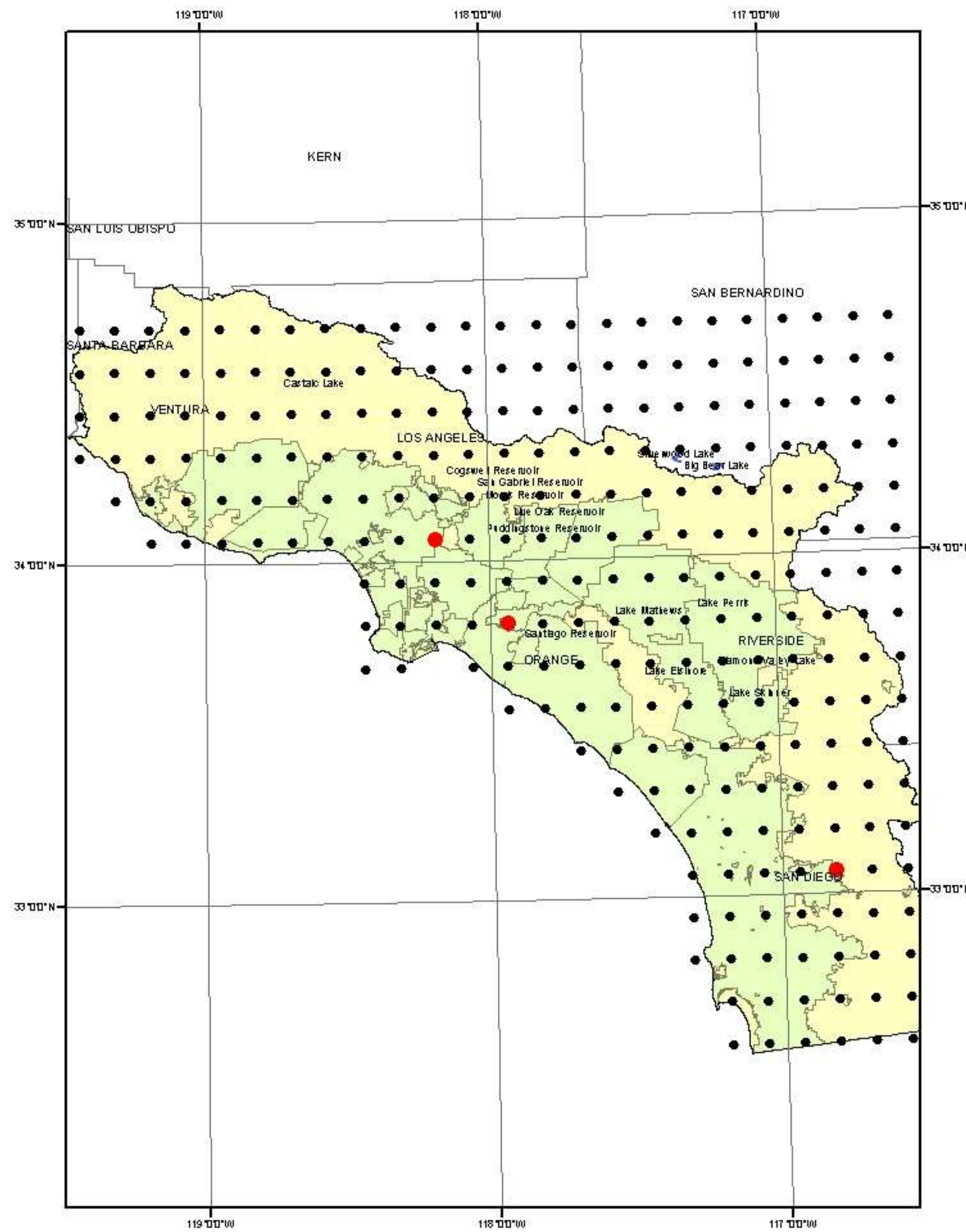


Figure 2: Centers for each data point overlying the MWD service area and watershed. Service area and watershed data courtesy of MWD. The red points indicate the three locations examined in more detail.

We selected three locations to perform some preliminary analysis of the historical and project data:

1. Orange County (over Anaheim)
   Lat: 33.8125
   Lon: -117.9375
2. Southern California (over Ramona)

Lat: 33.0625
Lon: -116.8125
3. Downtown Los Angeles
Lat: 34.0625
Lon: -118.1875

Climate projections and trend analysis

For each of the three locations, we appended the historical annual data from 1949-2000 to the projection data from 2001 – 2050 for each of the 12 CAT climate scenarios, as shown in Figure 3 through Figure 5.

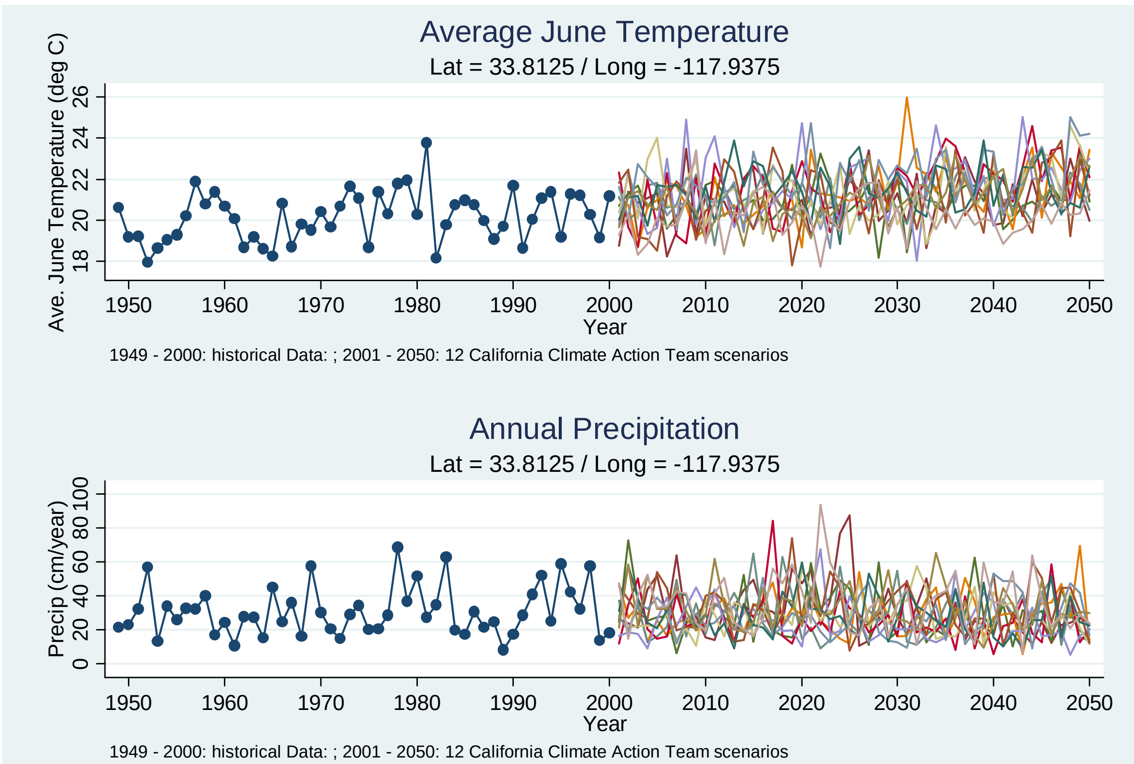


Figure 3: Time series of average June temperature (top) and annual precipitation for data point over Anaheim.

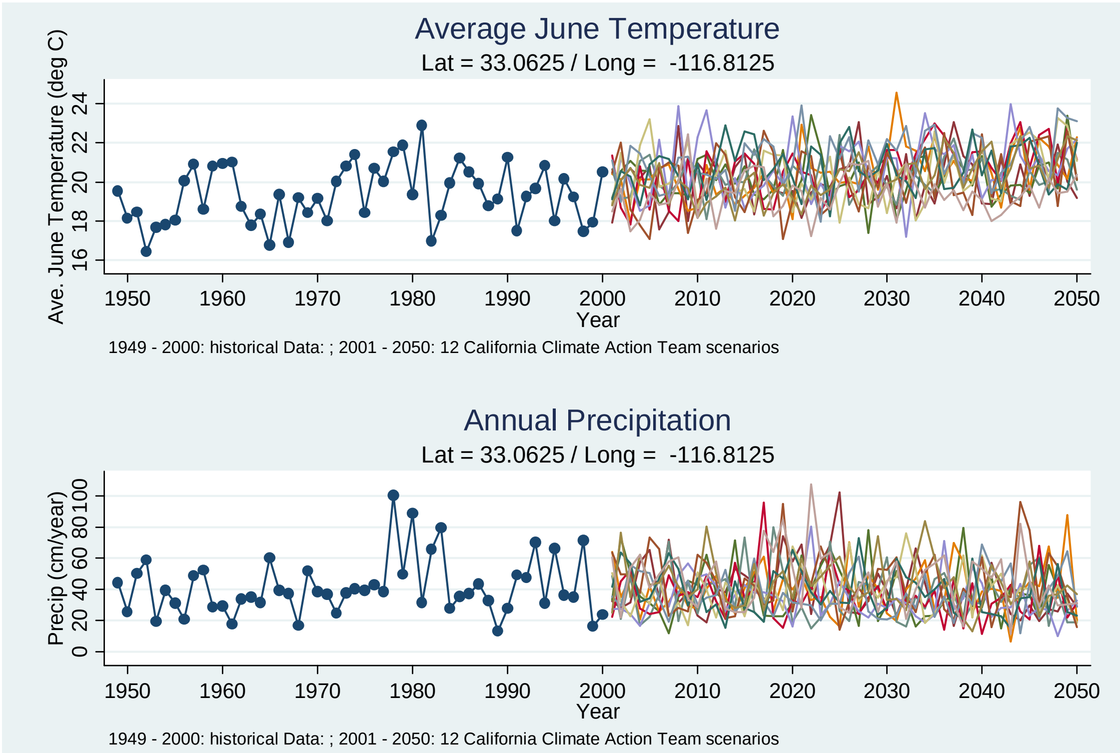


Figure 4: Time series of average June temperature (top) and annual precipitation for data point over Ramona.

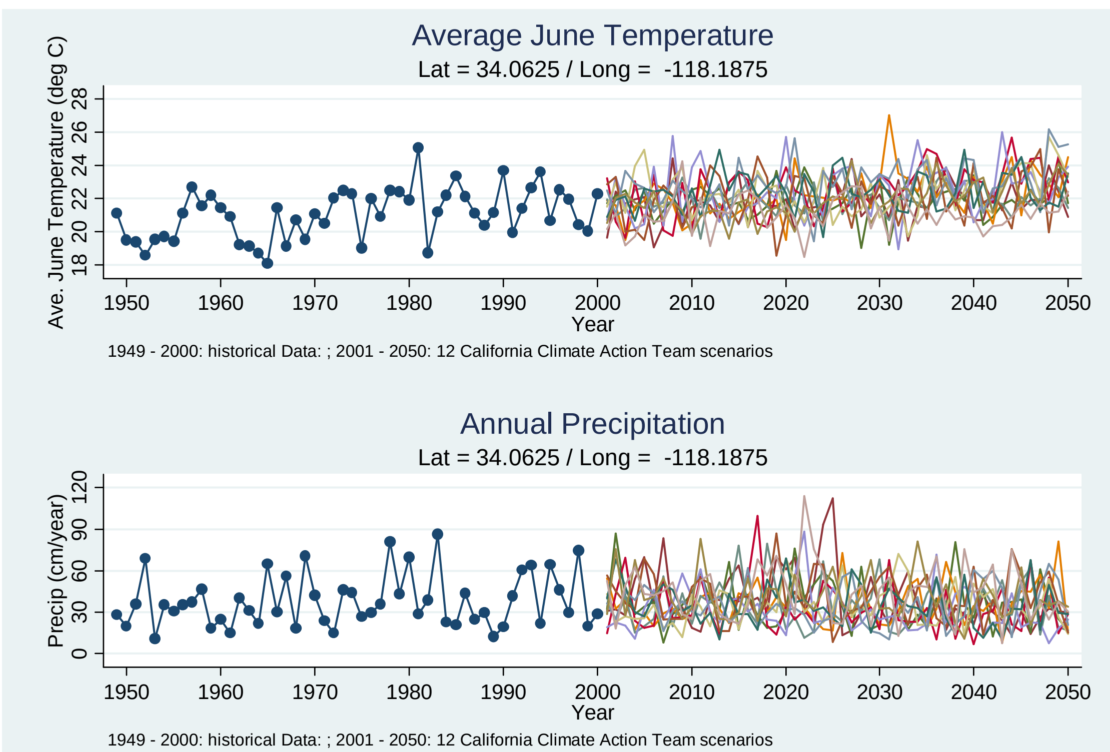


Figure 5: Time series of average June temperature (top) and annual precipitation for data point over Los Angeles.

For each location and climate sequence we then regressed year against the annual precipitation and average June temperature. The first coefficient can be interpreted as the average long-term annual change. We plotted the regression-derived trends (from 2000 to 2050) in precipitation against those in temperature for each of the 48 GCM / SRES model pairs. We also indicate the pairs that correspond to the CAT scenarios for the A2 and B1 SRES scenarios.

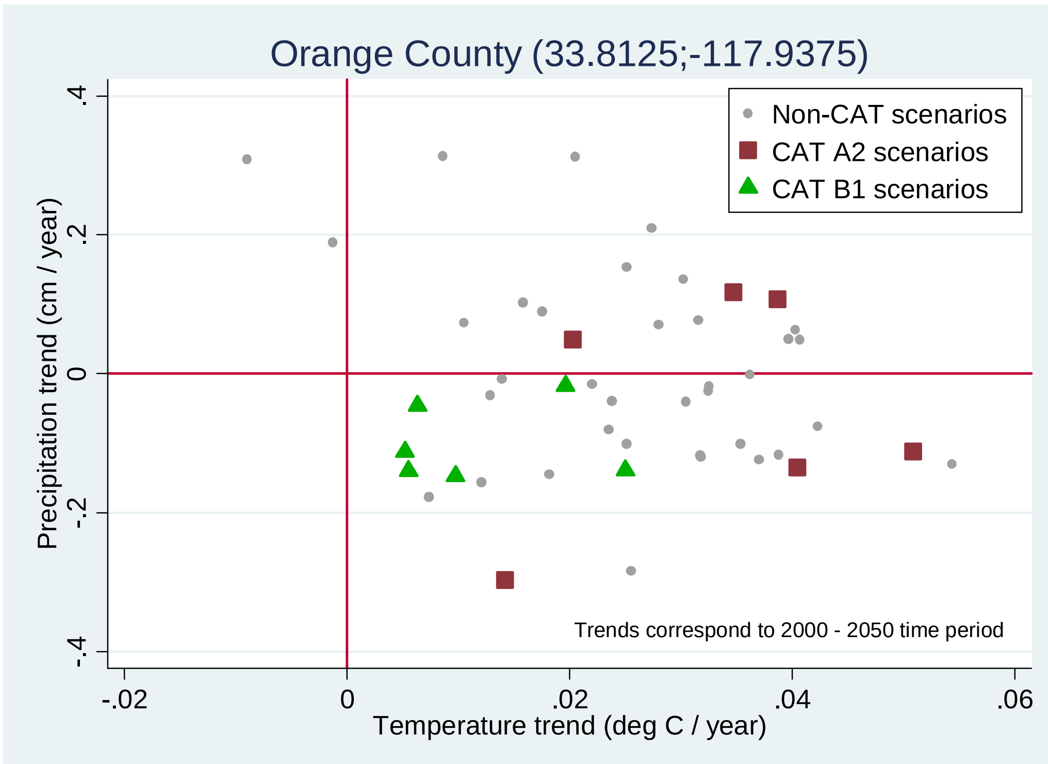


Figure 6: Temperature and precipitation trends for each climate projection (over Anaheim).

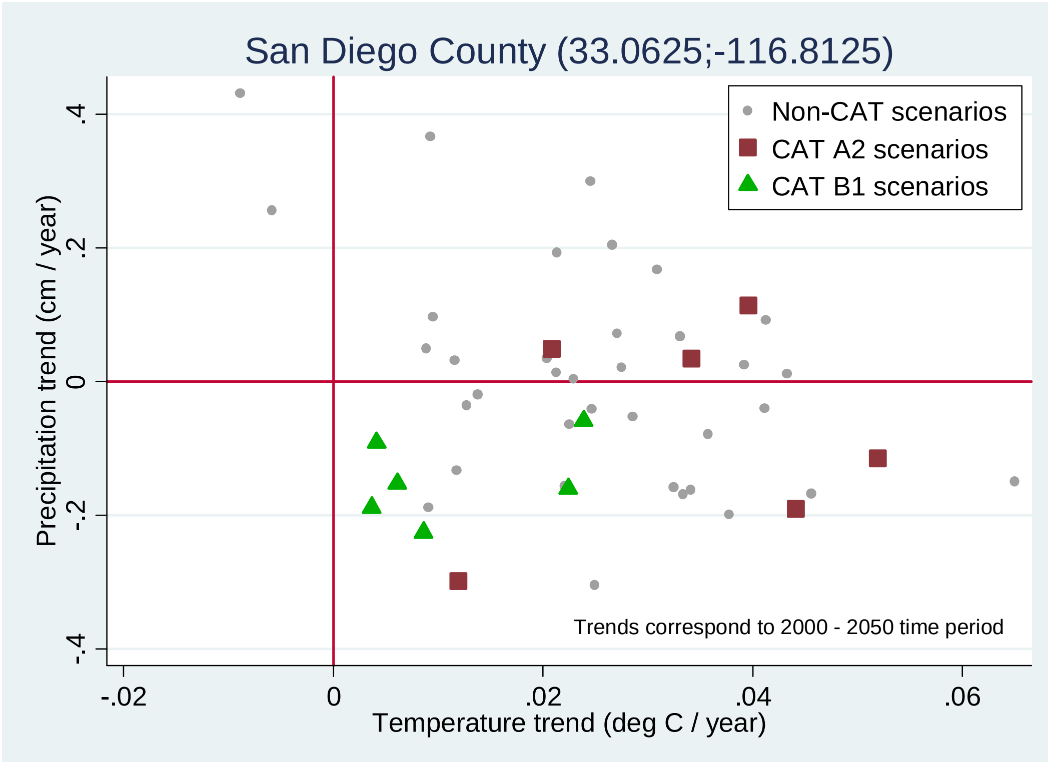


Figure 7: Temperature and precipitation trends for each climate projection (over Ramona).

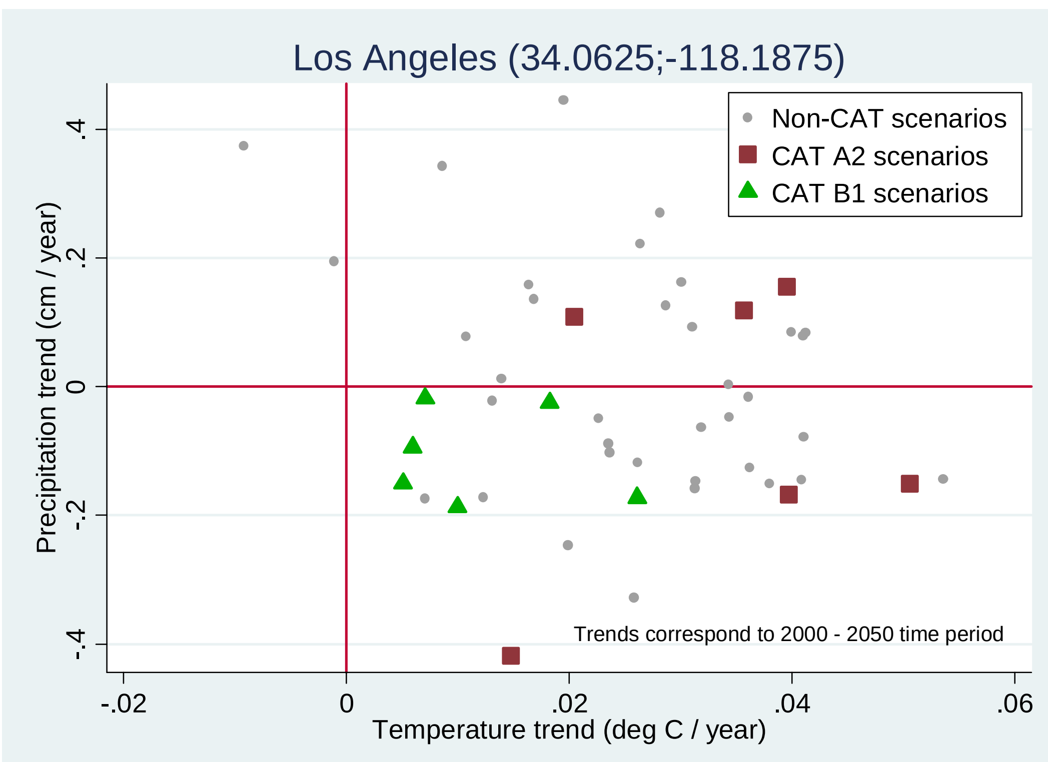


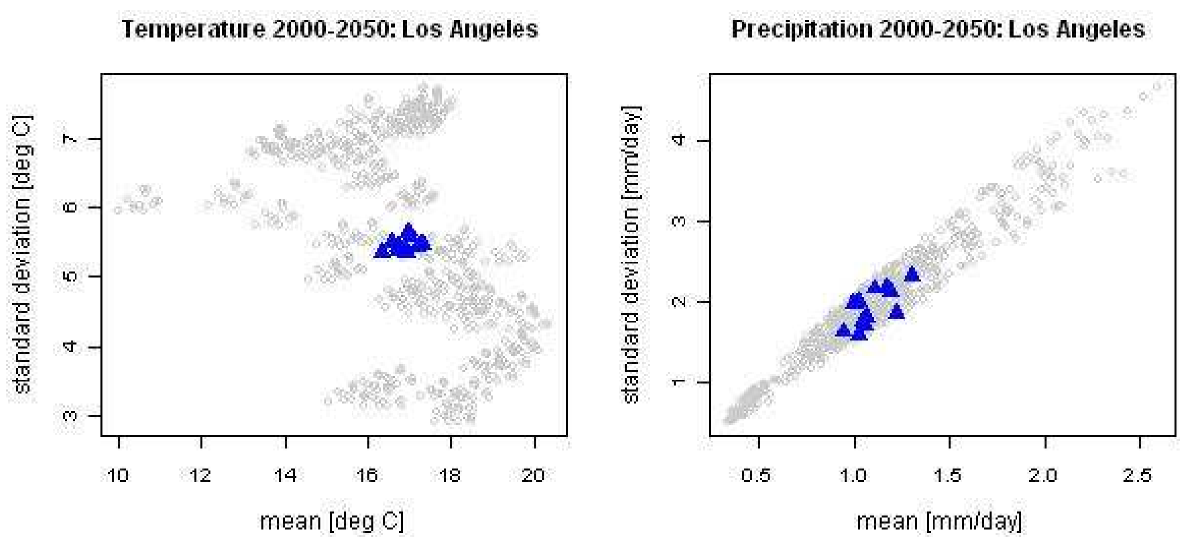
Figure 8: Temperature and precipitation trends for each climate projection (over Los Angeles).

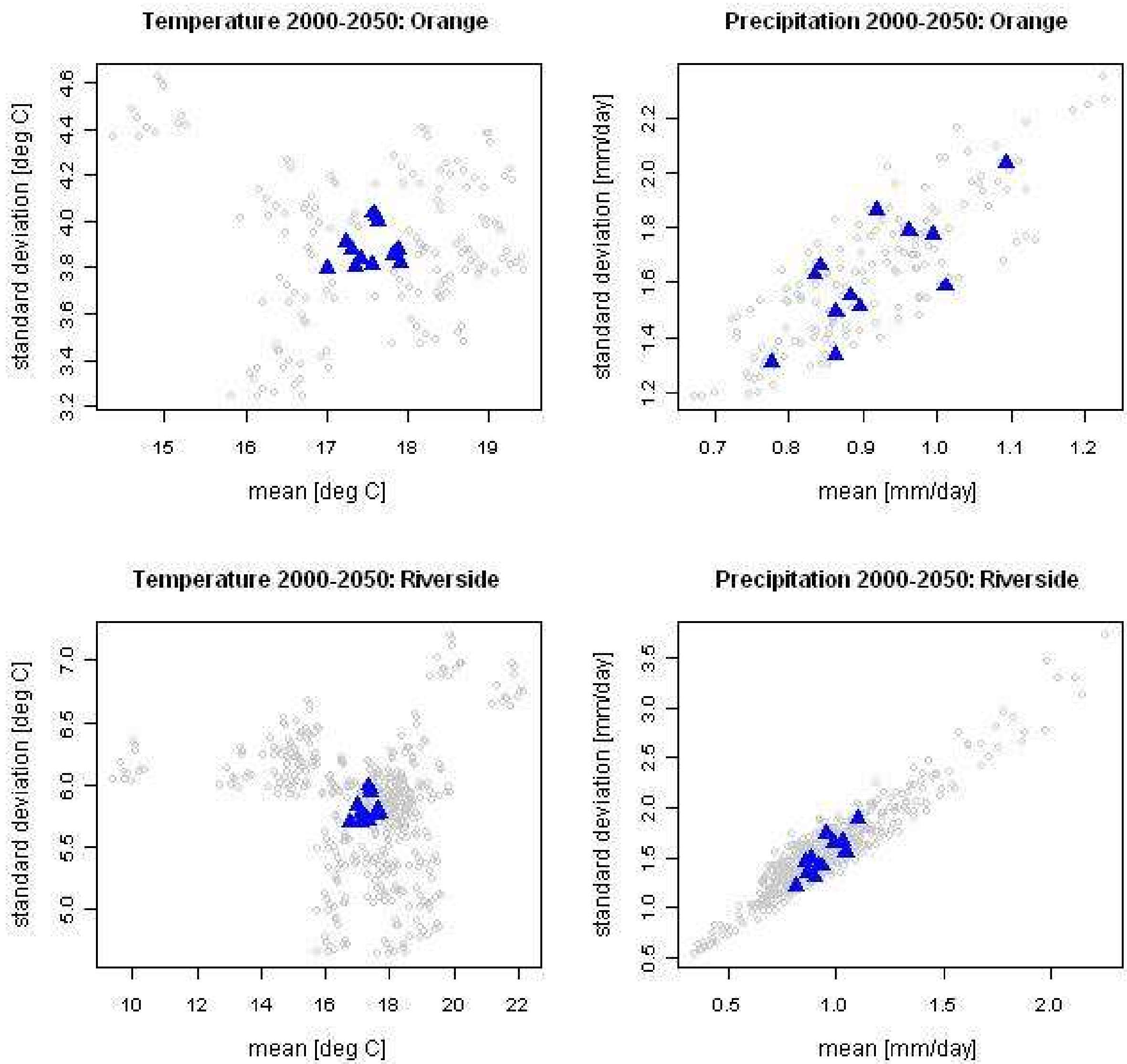
As the above figures suggest, there is significant variation in the projected future temperature and precipitation trends across the MWD service area. Almost all climate projections indicate warming temperatures, ranging from very modest warming to 2.5 degrees C warming between 2000 and 2050. Precipitation trends vary from significantly negative trends (declines of 20 cm over the 50 year period) to significantly positive trends (increases of 20 cm over the 50 year period). The CAT scenarios exclude the simulations that show cooling projections as well as the scenarios with significant positive trends in precipitation.

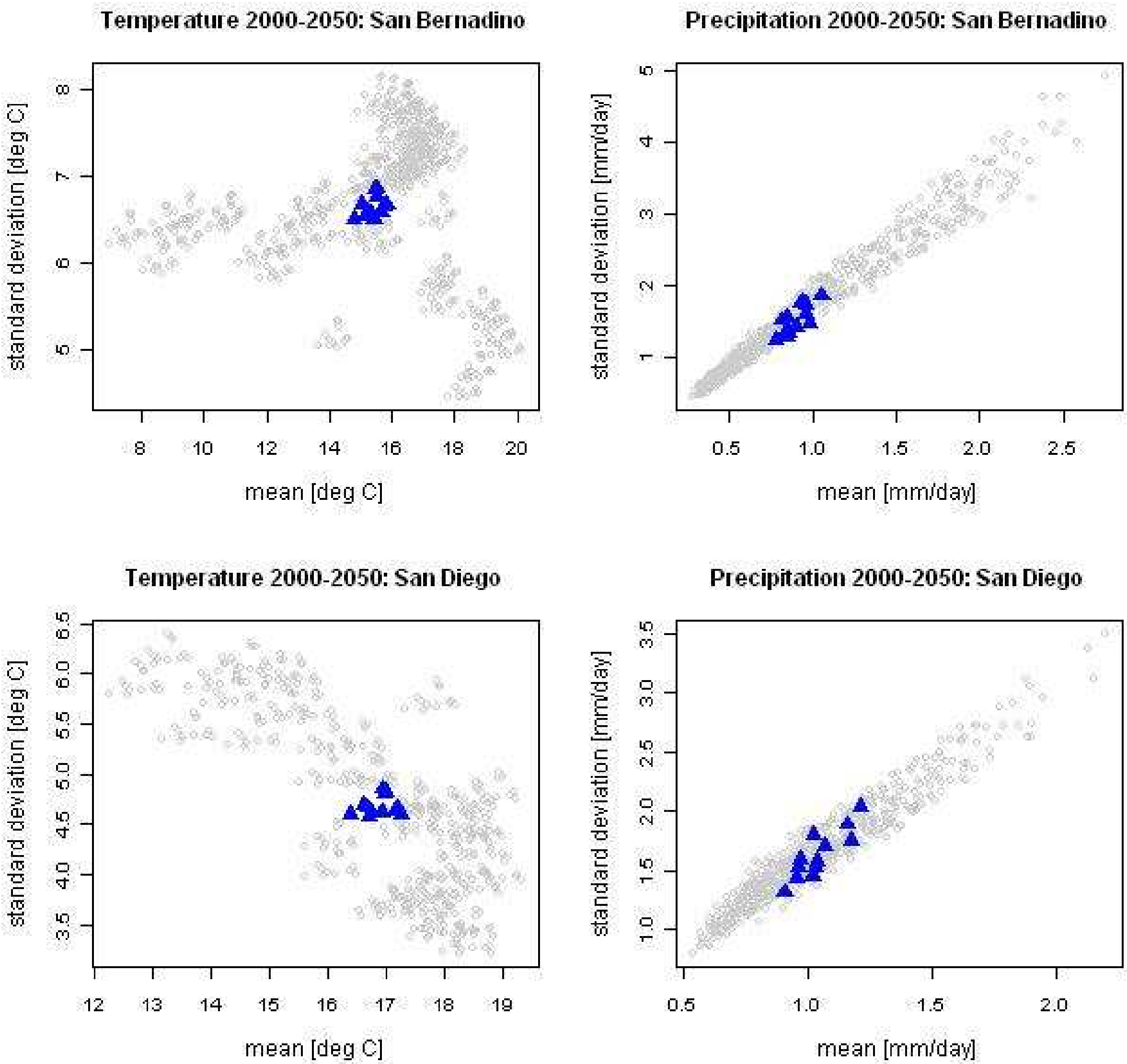
This analysis suggests that it would be difficult to develop a single projection to evaluate climate change in MWD's IRP and that the scenario approach will preserve the inherent uncertainty over future climate projections as evidenced by the GCM simulations.

Spatial averaging for demand analysis

To illustrate the impact of spatial averaging by county upon the overall statistics of the climate projections, we compare the mean and standard deviation for temperature and precipitation for the disaggregated and aggregated data. In the figures below, each gray circle shows for each 1/8 degree grid-point and CAT climate simulation (by county) the mean temperature (left plots) and mean precipitation (right plots) (x-axis); and the standard deviation of monthly temperature and precipitation (y-axis) for the 2000 to 2050 time period. The dark triangles show the same results for the county-averaged data for each of the 12 CAT scenarios.




Temperature 2000-2050: Orange
standard deviation [deg C]
mean [deg C]
Precipitation 2000-2050: Orange
standard deviation [mm/day]
mean [mm/day]
Temperature 2000-2050: Riverside
standard deviation [deg C]
mean [deg C]
Precipitation 2000-2050: Riverside
standard deviation [mm/day]
mean [mm/day]



Temperature 2000-2050: San Bernadino
standard deviation [deg C]
mean [deg C]
Precipitation 2000-2050: San Bernadino
standard deviation [mm/day]
mean [mm/day]
Temperature 2000-2050: San Diego
standard deviation [deg C]
mean [deg C]
Precipitation 2000-2050: San Diego
standard deviation [mm/day]
mean [mm/day]

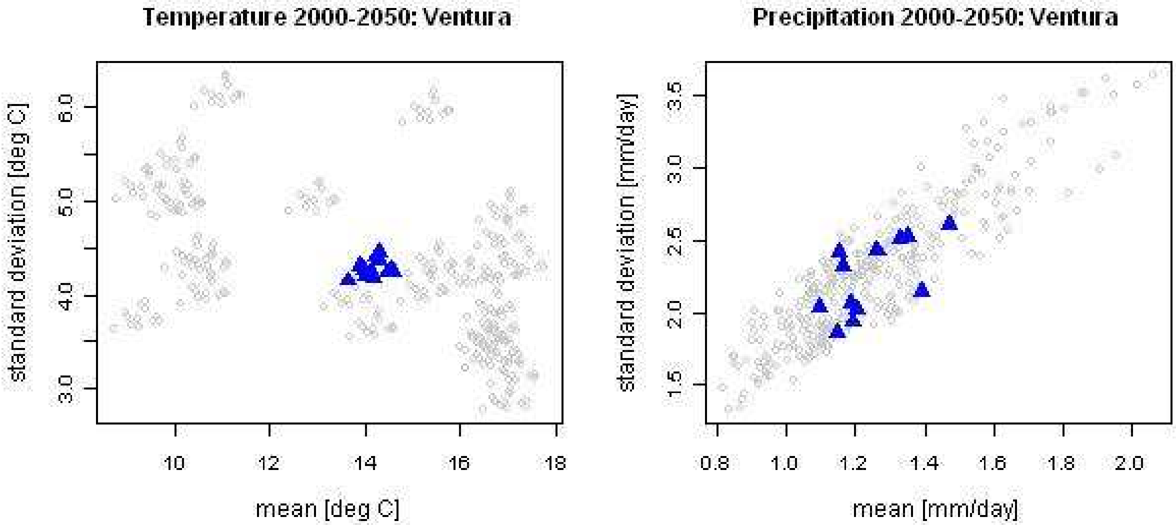


Figure 9: Mean and standard deviation of monthly temperature (left) and monthly precipitation (right) by county (each row) for 12 CAT scenarios and each 1/8 deg grid point within the county (gray circles) and for the county average by climate scenario (blue triangles).

These graphs show that there is significant variation in these key statistics across the individual climate sequences (gray circles). The statistics for temperature show no dominant pattern. The statistics for precipitation show that sequences with higher mean values are accompanied by higher variability. This is expected as there are always months with no precipitation and those areas with high total precipitation will necessarily have a wider range of monthly precipitation values than areas with lower total precipitation.

The relatively-tight clustering of the aggregated results (blue triangles) suggests that most of the variation is due to differences within scenarios across the different locations (e.g. 1/8 degree grid points). The pattern of results also shows that, in general, there is no loss in variability due to the averaging—the blue county-averaged data lie within the variability of the individual results. This is due to the high spatial correlation of non-aggregated data.

Our interpretation of these results is the following:

- There is significant spatial heterogeneity, therefore, only grid-points that represent regions of the county with significant demand should be included
- The high spatial correlation of results for each scenario allows aggregate results to preserve the inherent variability of the disaggregated results.

We next identify the grid points that correspond to the urban areas within each county. Note that for Santa Barbara, only three grid points are within the larger MWD local watershed and are all non-urban, thus we make no changes to the included grid points. The figure below shows the 2006 National Land Cover Data set for Southern California with the 1/8 degree climate grid overlaid. The black circles indicate those deemed to represent significant urban area.

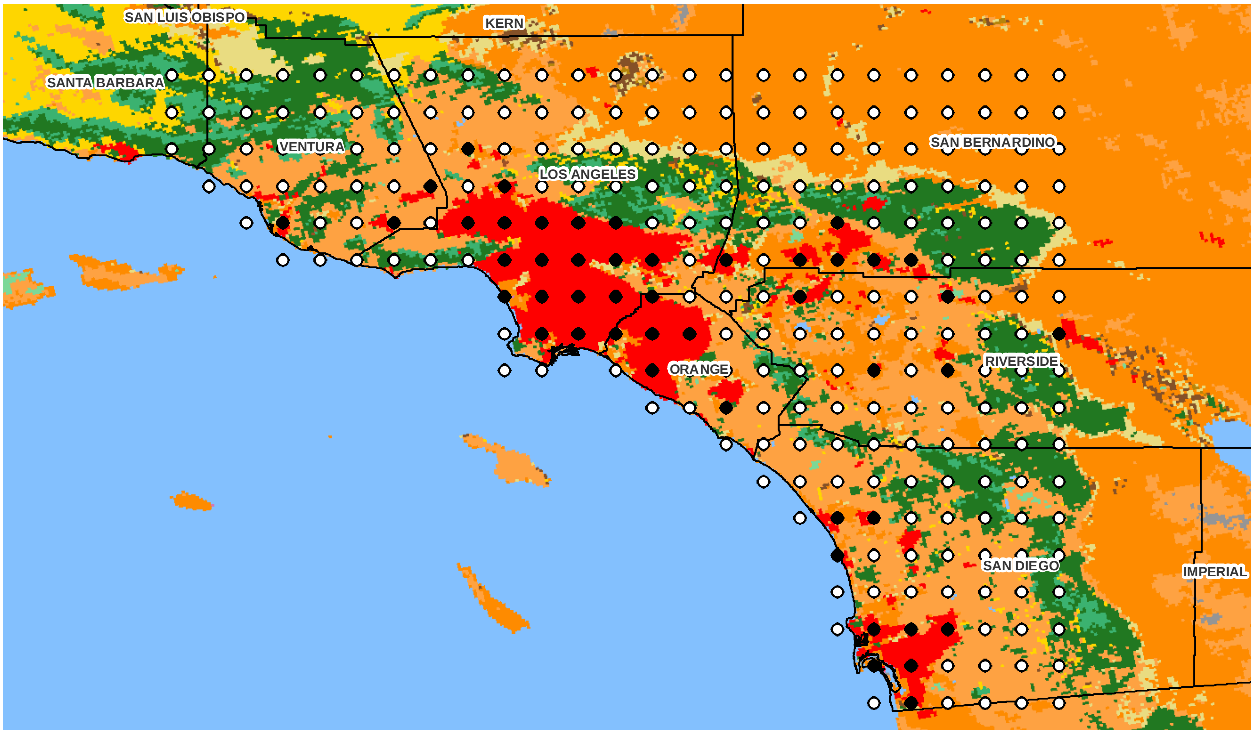
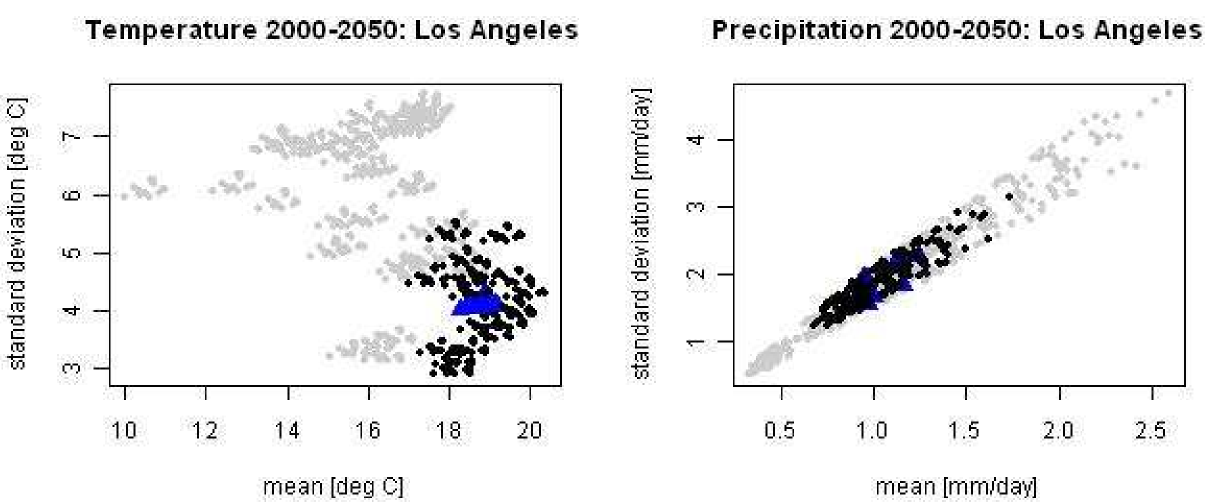
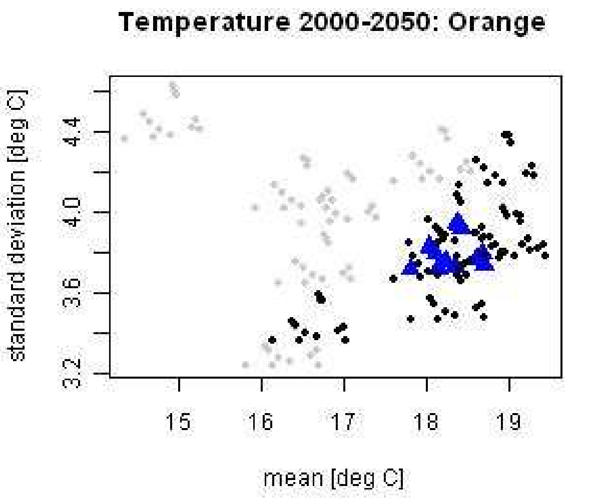
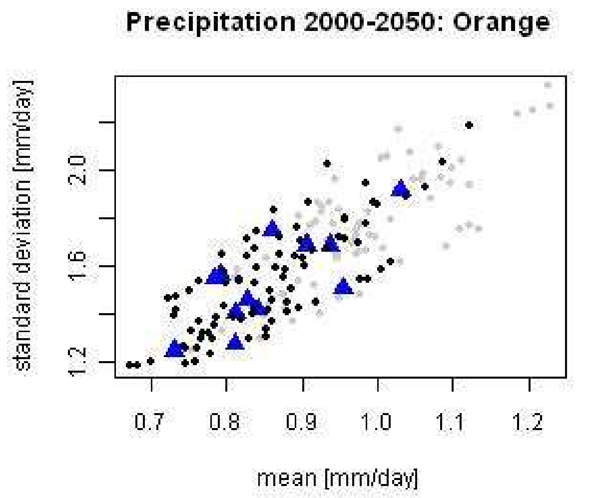


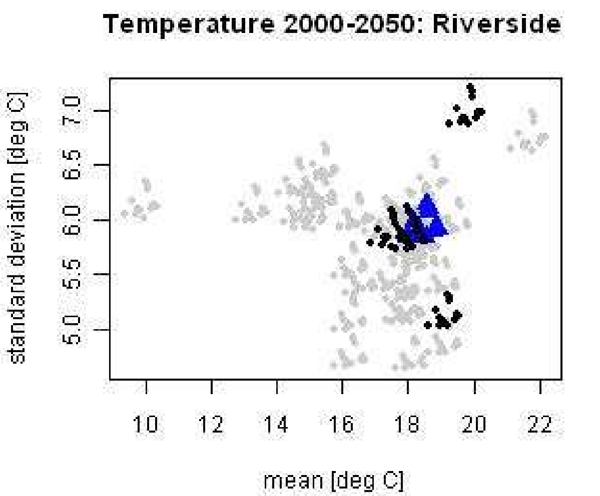
Figure 10: 2006 National Land Cover Data set for Southern California with 1/8 deg climate grid.

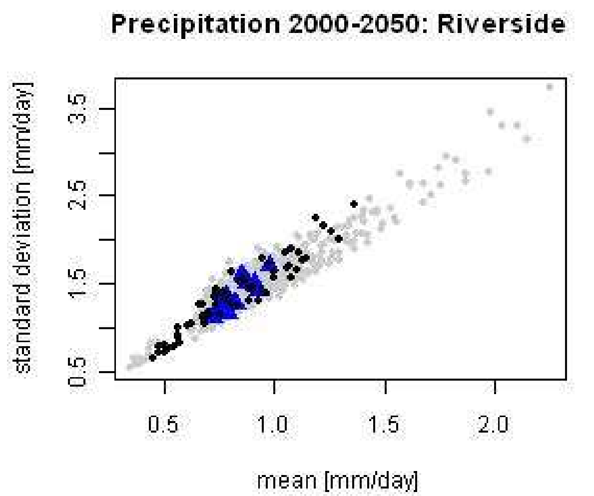
Below we show the same scatter plots as above, except that we use only grid-points that correspond to high urban density to compute the county-mean values (shown as black dots). As can be seen, the spatial heterogeneity of the urban results is significantly lower and we can be more confident that the spatially-average climate data are representative of the regions of the service area where water demand is concentrated.

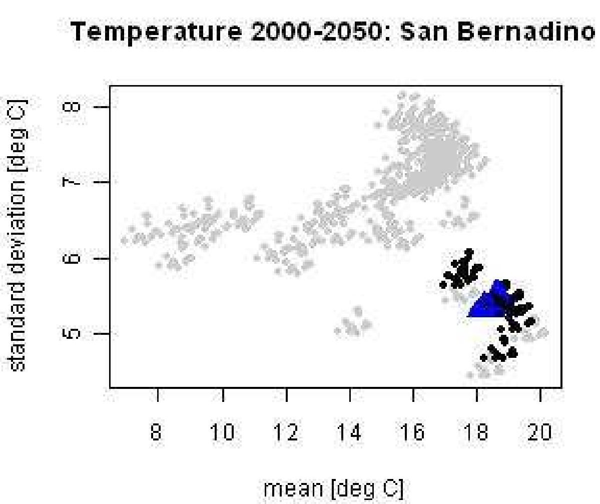


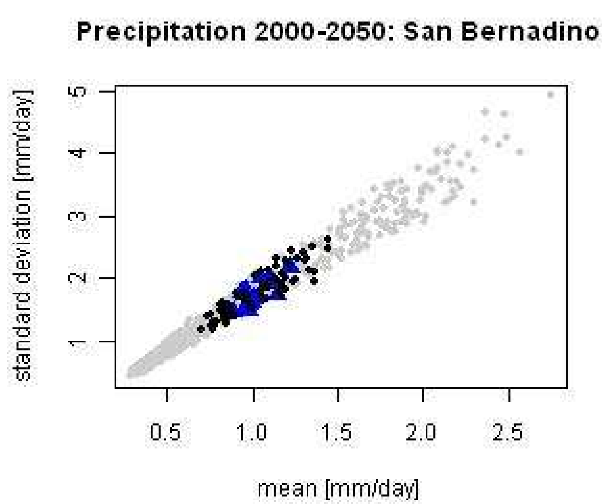

Temperature 2000-2050: Orange
standard deviation [deg C]
mean [deg C]


Precipitation 2000-2050: Orange
standard deviation [mm/day]
mean [mm/day]


Temperature 2000-2050: Riverside
standard deviation [deg C]
mean [deg C]


Precipitation 2000-2050: Riverside
standard deviation [mm/day]
mean [mm/day]


Temperature 2000-2050: San Bernadino
standard deviation [deg C]
mean [deg C]


Precipitation 2000-2050: San Bernadino
standard deviation [mm/day]
mean [mm/day]

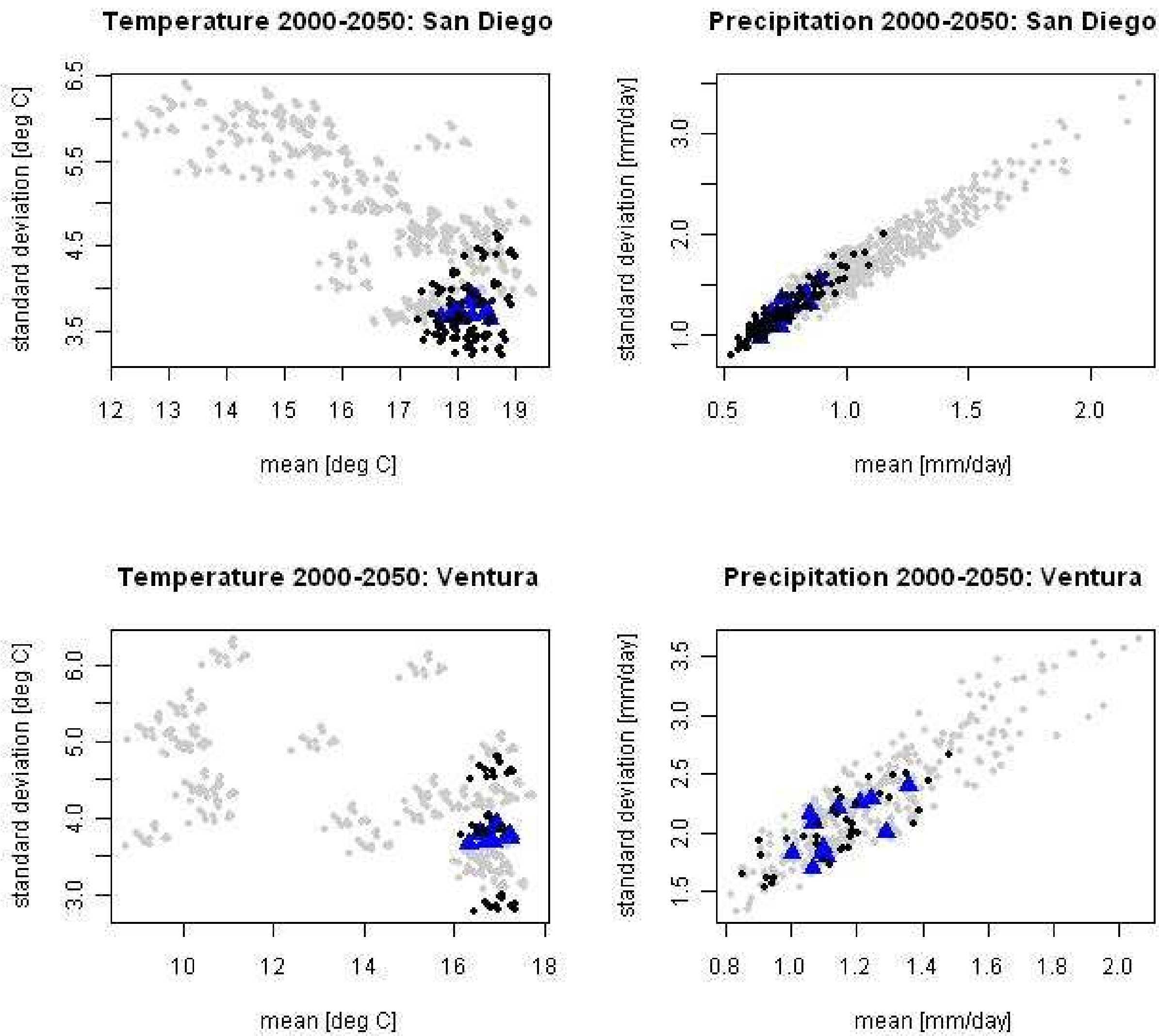


Figure 11: Mean and standard deviation of monthly temperature (left) and monthly precipitation (right) by county (each row) for 12 CAT scenarios and each 1/8 deg grid point within the county for non-urban area (gray circles) for urban areas (black circles) and for the urban area county average by climate scenario (blue triangles).

Data Format

The consulting team will provide two sets of climate data for all locations (and county averages) to MWD in easy-to-use comma-separated text formats. The first set of sheets will include monthly data for the historical period (1950-2000) and for the projection period (2000-2050) for a single location or county average. Each data row will provide the following data for each location (specific 1/8 degree location or county-average):

- Year
- Month
- GCM name

- SRES emissions scenario
- CAT scenario indicator (1-12 and NULL for non-CAT scenario)
- Monthly precipitation value [mm/month]
- Monthly average temperature value [deg C]
- Annual precipitation [mm/year]
- Annual average temperature [deg C]
- County

The second set of climate data files will include 45 sequentially-indexed time series of annual temperature and precipitation for the projection period 2005-2050. These files will include the following data for each location (specific 1/8 degree location or county-average):

- Year
- Offset (in years)
- GCM name
- SRES emissions scenario
- CAT scenario indicator (1-12 and NULL for non-CAT scenario)
- Annual precipitation [mm/year]
- Annual average temperature [deg C]
- County

RAND will initially provide the county-averaged data for the 12 CAT scenarios. After the MWD staff has identified other locations (on the 1/8 degree grid) for which data is needed, RAND will provide the corresponding data files.

References

Cayan, D., Maurer, E., Dettinger, M., Tyree, M., Hayhoe, K., Bonfils, C., Duffy, P., and Santer, B. (2006). "Climate Scenarios for California." *CEC-500-2005-203-SF*, California Climate Change Center.

Groves, D. G., Yates, D., and Tebaldi, C. (2008). "Developing and Applying Uncertain Global Climate Change Projections for Regional Water Management Planning." *Water Resources Research*, forthcoming.

Maurer, E. P., Wood, A. W., Adam, J. C., Lettenmaier, D. P., and Nijssen, B. (2002). "A Long-Term Hydrologically-Based Data Set of Land Surface Fluxes and States for the Conterminous United States." *Journal of Climate*, 15, 3237-3251.